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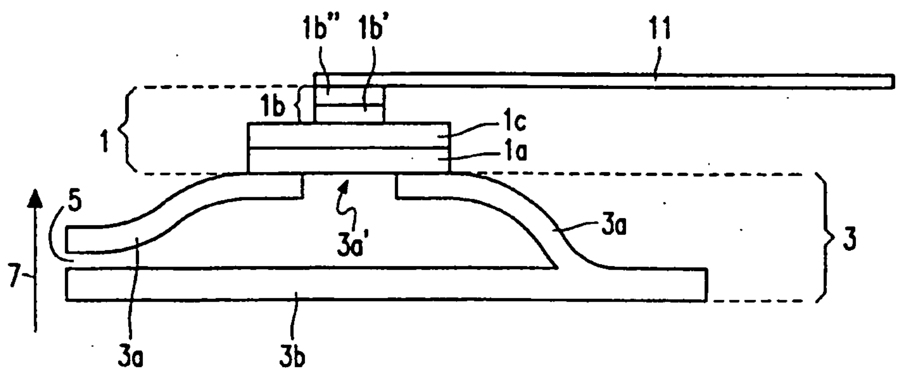

(57) Abstract

A magnetic field sensor comprising a transducer element (1), whereby: (I) the transducer element (1) is a Spin Tunnel Junction, comprising a first (1a) and second (1b) magnetic layer which are sandwiched about an interposed electrical insulator layer (1c); (II) the sensor comprises a yoke (3) having two arms (3a, 3b); (III) the first magnetic layer (1a) is in direct contact with a first portion of a first arm (3a) of the yoke (3).

"Magnetic field sensor comprising a spin-tunnel junction"

The invention relates to a magnetic field sensor comprising a transducer element. Such sensors may be employed *inter alia*:

- as magnetic heads, which can be used to decrypt the magnetic flux emanating from a recording medium in the form of a magnetic tape, disc or card;
- in compasses, for detecting the terrestrial magnetic field, *e.g.* in automotive, aviation, maritime or personal navigation systems;
- in apparatus for detecting position, angle, velocity or acceleration, *e.g.* in automotive applications;
- as field sensors in medical scanners, and as replacements for Hall probes in various other applications;
- as current detectors, whereby the magnetic field produced by such a current is detected.

Sensors as specified in the opening paragraph are well known in the prior art. The transducer element in such sensors typically comprises a magneto-resistance element, which translates magnetic flux variations into a correspondingly fluctuating electrical resistance R; a measure of the performance of the element is then expressed in the so-called magneto-resistance (MR) ratio, which quantifies the maximum change in R as a function of applied magnetic field. Sensors of this type may be based on one of the following effects:

- The Anisotropic Magneto-Resistance effect (AMR), whereby R in a magnetic body is dependent on the orientation of the body's magnetization with respect to the direction of electrical current flow through the body; or
- The Giant Magneto-Resistance effect (GMR), whereby R is determined by the relative orientation of the magnetization vectors in two distinct magnetic bodies, for example:

  - two layers which are sandwiched about an interposed metallic layer (interlayer), thus forming a so-called spin-valve trilayer (see, for example, the

measurement current is directed parallel to the plane of the element; on the other hand, in an STJ, the measurement current must be directed (tunneled) across the interlayer, and so is directed perpendicular to the plane of the element. These differences help account for the most dramatic advantages of an STJ: because of the STJ's high tunnel resistance, the measurement current can afford to be very small (of the order of 1 about μA, or less), and the room-temperature, low-field MR-ratio of an STJ is routinely of the order of at least 15%.

The term "magnetic layer" as used with reference to an STJ should be broadly interpreted. Such a magnetic layer may, for example, be comprised of one of the following:

- a single layer of ferromagnetic material;
- a ferromagnetic film which is accompanied by a thin, metallic, non-magnetic film on the side adjacent to the nearest yoke-arm;
- two ferromagnetic films which are exchange-coupled across an interposed electrically conducting film;
- a ferromagnetic film which is arranged in a stack with a pinning structure (examples of which are given herebelow in Embodiment 1), the pinning structure serving to directionally fix the magnetization in the adjacent ferromagnetic film.

In all cases, it is important to realize that the magnetic layer does not contain any electrically insulating films; the only electrically insulating structure in the STJ is the tunnel barrier (interlayer) between the first and second magnetic layers.

When a AMR or GMR transducer element is employed in a yoke-type magnetic field sensor, the element is electrically insulated from the yoke, *e.g.* by the use of a so-called separation-oxide layer between the element and the yoke; this is to prevent the yoke-arm from acting as an electrical shunt around the transducer element (in which, as has already been explained, the measurement current is parallel to the plane of the element and also to the top surface of the yoke-arm). However, the presence of an insulating layer between the yoke and the transducer element reduces the magnetic contact between the two, which accordingly reduces the efficiency of the sensor. This acts as a deterrent to the use of a yoke in conjunction with conventional sensors. In contrast, the inventors have realized that, when an STJ is employed instead of a conventional magneto-resistance transducer element, the use of a yoke becomes a more viable possibility. This is because the measurement current through the STJ is directed perpendicular to its plane, so that a yoke-arm in electrical contact with one of the magnetic layers of the STJ does not act as an electrical shunt around the

even further if the thickness t_2 of the second portion of the second arm of the yoke is also less than the thickness of the rest of the second arm immediately adjacent thereto; in that case, magnetic flux also becomes more concentrated in the second portion, causing a further increase in sensitivity of the sensor.

The skilled artisan will immediately appreciate that, if the STJ is to be useful as a sensor, the respective magnetizations M_1, and M_2 in the first and second magnetic layers must change their relative orientation as a function of applied magnetic field. This can, for example, be achieved by employing different magnetic materials in the two layers, or by ensuring that M_1 and M_2 are mutually perpendicular in the quiescent state (*e.g.* using exchange biasing). As an alternative, a particular rendition of the embodiments described in the previous paragraph is characterized in that $t_2 > t_1$. In such an embodiment, the discrepant values of t_1 and t_2 result in different flux concentrations in the first and second yoke-arms, respectively, so that, when a given external magnetic field is offered to the yoke, M_1 and M_2 will rotate to different extents. Good results are achieved for sensors in which the value of t_2/t_1 lies in the range 2-30, with particularly good results at $t_2/t_1 \cong 10$.

In addition to the transducer and the yoke, the sensor according to the invention may comprise various other structures. For example:

- in the case whereby only one of the magnetic layers of the STJ is in contact with the yoke, the other magnetic layer of the STJ will have to be provided with an electrical contact lead;
- a test/biasing conductor may be provided (e.g. as illustrated in Figure 4).

The invention and its attendant advantages will be further elucidated using exemplary embodiments and the accompanying schematic drawings, whereby:

Figure 1 renders a cross-sectional view of a particular embodiment of a magnetic field sensor according to the invention, and shows a yoke-type magnetic field sensor comprising an STJ;

Figure 2 shows a variant of the subject of Figure 1, whereby a portion of one of the arms of the yoke constitutes one of the magnetic layers of the STJ;

Figure 3 illustrates a variant of the subject of Figure 2, whereby the said portion is of reduced thickness relative to the rest of the yoke-arm;

Figure 4 depicts a variant of the subjects of Figures 2 and 3, whereby the role of both magnetic layers of the STJ is played by different thinned arms of the yoke.

As here depicted, the magnetic layer 1b has a composite structure, and comprises a ferromagnetic film 1b' which is arranged in a stack with a pinning structure 1b". The (metallic) pinning structure 1b" serves to directionally "fix" the magnetization M_2 in the film 1b'; to this end, it may, for example, comprise one or more of the following:

- An antiferromagnetic material, such as $Fe_{50}Mn_{50}$. In this case, M_2 is fixed by means of exchange biasing with the film 1b";
- A hard-magnetic ferromagnetic material, such as Co. In this case, M_2 is fixed purely by the coercive force exerted by the magnetization of the film 1b";
- A so-called artificial antiferromagnetic (AAF) structure. The structure 1b" is then a stack comprising a permanent-magnetic film F which is separated from the film 1b' by an interposed metallic film M. In this case, M_2 is fixed predominantly by exchange coupling with the film F across the layer M.

Since M_2 is fixed in this manner, whereas the magnetization M_1 in the layer 1a is free, it is possible to alter the relative orientation of M_1 and M_2 under the influence of an external magnetic field. This, in turn, induces corresponding alterations in the electrical resistance of the trilayer 1a,1b,1c, which are measured with the aid of the measurement current passing through the STJ 1 between the contact 3a and the contact 11. In a particularly sensitive embodiment, M_1 and M_2 are biased so as to be mutually perpendicular in the quiescent state.

<u>Embodiment 2</u>

Figure 2 depicts a variant of the subject of Figure 1. In this variant, the role of the discrete first magnetic layer 1a in Figure 1 is assumed by a first portion of the first yoke-arm 3a (this first portion 1a is hatched in Figure 2). As a result, the magnetic gap 3a' in Figure 1 becomes unnecessary, and the yoke-arm 3a is now, therefore, continuous. This simplifies manufacture of the sensor, since:

- fewer layers are required (there is no discrete layer 1a necessary);
- there is no magnetic gap 3a'.

<u>Embodiment 3</u>

Figure 3 shows a variant of the sensor in Embodiment 2. In this variant, the yoke-arm 3a has been thinned in the vicinity of the layer 1c. The thickness t_1 of the

medium (which is caused to pass before the gap 5). In one specific embodiment, the layer 1a extends continuously along A, whereas the layers 1b,1c extend along A as a series of discrete bi-layer stacks, each being positioned atop the layer 1a so as to positionally correspond to an individual track.

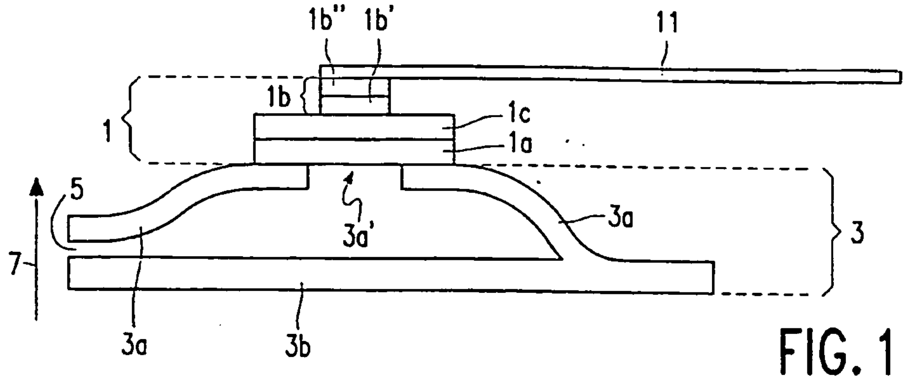

FIG. 1

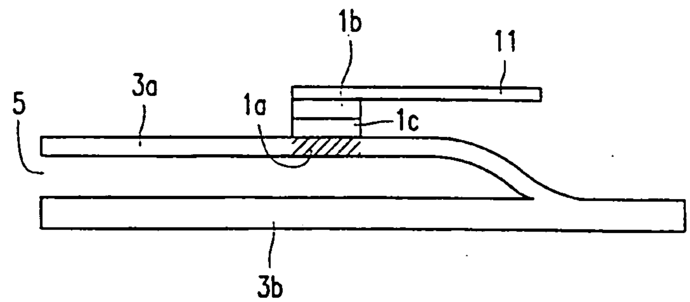

FIG. 2

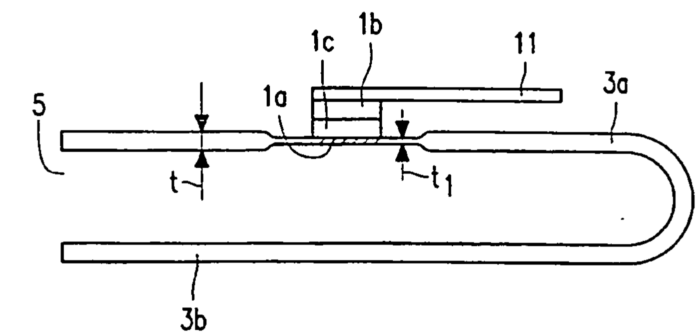

FIG. 3

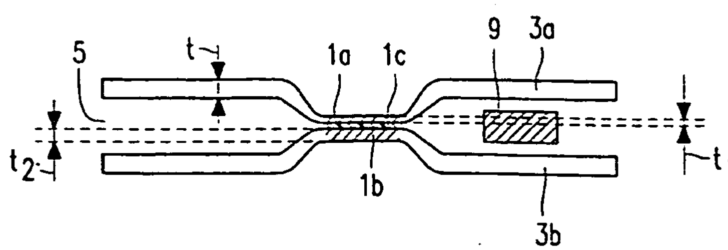

FIG. 4